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A State-of-the-Art Survey of Radio Frequencies Available for Tactical Battlefield Radios in Frequency Bands Above 30 MHz

by Alan R. Downs

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Abstract

The combat radio used by the fighting units (battalion and below) of the U.S. Army is the Single-Channel Ground/Air Radio System (SINCGARS). This radio system operates effectively except that the available bandwidth is insufficient to avoid channel congestion on digital channels, resulting in low throughput and long delays in ordinary tactical situations. This report describes one of a pair of studies that addressed one possible way to ameliorate this situation, i.e., changing the frequency at which the basic combat radio operates. This study addresses taking advantage of the higher bandwidth available in higher frequency parts of the radio frequency spectrum. The procedure entailed addressing the technological and environmental factors that affect radio operations at frequencies between 30 MHz and 100 GHz for several modes of operation, i.e., direct transmission, terrestrial relay, and satellite relay. The most favorable such system is then compared to the SINCGARS system. Several conclusions and recommendations are then presented.

ACKNOWLEDGMENTS

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1. INTRODUCTION

The objective of the study culminating in this report is to perform a state-of-the-art survey to identify those parts of the radio frequency spectrum that are likely to become available for land/air mobile battlespace communication. Assess the technical characteristics of promising channels, i.e., identify those characteristics that could impede or inhibit their use for wide-band, multimedia communications. In performing this study, the first task was to perform a literature search for reports, articles, and U.S. Army Research Laboratory (ARL) Foreign Intelligence Office (FIO) translations of foreign reports and articles. The search limits were made sufficiently wide that anything pertaining to the subject area should be included. As a result, over 1,500 abstracts were reviewed for pertinence. Of these, 112 seemed sufficiently relevant that the entire article was reviewed. Of this number, about half had enough relevance to this study that information contained therein was included in this report.

Some of the entries on the list of references are noticeably old—even dating back to the 1960s. This is not surprising in a study of this nature since, although actual systems operating in frequency bands of interest may be a recent development, the environment in which such systems must operate is not. A great deal has been known for decades about such things as atmospheric propagation and terrain obscuration, and it seemed sensible to go to the basic sources and update as needed rather than cite more recent sources and skip some of the background needed for a basic understanding of some highly pertinent information areas.

In any study of this nature, a number of assumptions have to be made in order to limit the scope in a meaningful way. In this study, several such assumptions were made. These assumptions are:

- *The frequencies of interest are those higher than 30 MHz (i.e., the VHF/UHF/EHF bands).* Since mobile communication platforms are of particular interest, it is desirable to limit the size of antennas as much as possible, thus the importance of higher frequencies.

- *The transmission ranges of interest are those associated with fighting units (battalion and below) and probably, except for air operations, will not exceed several tens of kilometers.* The military is extremely diverse in its communications requirements, and the analysis of all such requirements is well beyond the scope of a quick study. Thus, it was decided to focus primarily on Army operations in a battlefield setting.

- *The technical, rather than the political, possibilities were explored.* The allocation of broadcast frequencies is a decision that is political in nature, i.e., the decision is out of the hands of the military. There is extreme competition for the optimum channels, and, although allocations have been made and systems are operating throughout the frequency range of interest, their assignment of operating frequencies can be changed based on technical, strategic, or financial considerations.

- *The option of satellite relay of transmissions was left open.* That is, this mode of operation was considered in parallel with ground-ground direct and relay modes.

- *All communication systems to be addressed are frequency modulated (line of sight) systems.*

2. THE RADIO SPECTRUM

The radio spectrum has been divided for convenience into a set of bands and subbands. These are presented in Table 1, most of the information in which was taken from Dorf (1933) with several additions included for completeness.

Sundaram (1988) puts a different slant on band usage—namely, that HF is used for strategic and long-range tactical traffic and that VHF/UHF bands are used for short-range battlefield communications. It further notes that the VHF/UHF bands are line-of-sight limited and that this can impose (possibly) severe communications restrictions and that satellite links can offset much of this problem. Also, the EHF band offers promise since:

- Channel capacity is almost unlimited;

- Beams are so narrow that monitoring/jamming is very difficult;

- Components are smaller, and therefore portable vehicular terminals are easier to develop.

These bands are shown schematically in Figure 1.

Table 1. Usage of Frequency Bands in the Radio Spectrum

Band	Subband	Frequency	Usage
HF	—	3 to 30 MHz	—
VHF	—	30 to 300 MHz	—
UHF	—	300 to 1,000 MHz (1 GHz)	—
EHF	—	1 GHz and greater	—
	L	1 to 2 GHz	Long-range surveillance.
	S	2 to 4 GHz	Long-range surveillance.
	C	4 to 8 GHz	Long-range weather characterization; terminal traffic control.
	X	8 to 12 GHz	Fire control; air-to-air missile seekers; marine radar; airborne weather characterization.
	Ku	12 to 18 GHz	Short-range fire control; remote sensing.
	Ka	27 to 40 GHz	Remote sensing; weapon guidance.
	V	40 to 75 GHz	Remote sensing; weapon guidance.
	W	75 to 110 GHz	Remote sensing; weapon guidance.

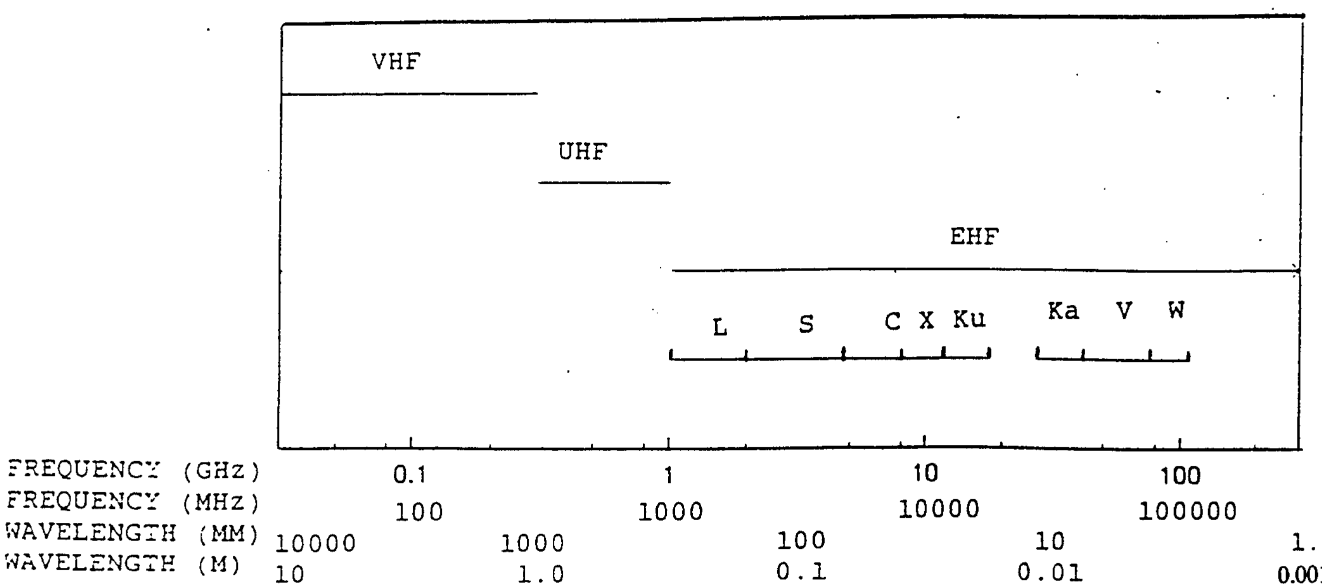

Figure 1. Schematic of the radio frequency spectrum.

3. LIMITATIONS TO SUCCESSFUL COMMUNICATION

In trying to propagate information from point to point, there are a number of limitations. Some of these limitations (e.g., adequate transmitters and receivers, jamming, robust protocols, and error correction techniques, etc.) are technological in nature. Others (e.g., atmospheric and terrain factors, fading, interference, and multipath effects, etc.) are more basic in nature and must be overcome before successful communications are possible. The pertinent factors will be addressed in turn in this section. Since many of these factors are, interrelated, the order in which they are addressed is dictated by convenience rather than by priority.

3.1 Atmospheric Considerations. Before addressing the effect of the atmosphere on communications, it should be noted that those who are expert in radar/radio frequency communications tend to describe the attenuation characteristics of the atmosphere in terms of decibels (dB) per kilometer. Those whose background is in optics tend to think of a transmission (T) characterized by an atmospheric attenuation coefficient, σ, operating over a given distance, r. These terms are related in the following manner:

$$T = \exp(-r\sigma) \qquad \mathrm{dB/km} = -10 \log_{10}(T)/r.$$

Figure 2 illustrates the way these variables are related.

The second scale on the abscissa provides an aid in interpreting this graph by remembering that the visibility is defined as the distance at which a sufficiently large black panel can be seen with 50% probability against the horizon sky. It is related to the variables in Figure 2 by the relationship: visibility = 3.912/σ, where 3.912 is the natural logarithm of 50 and 50 is the reciprocal of 0.02, the nominal contrast threshold of the human eye under daylight conditions (Middleton 1958).

The characteristics of the interaction of radio frequency signals with the atmosphere are so dependent on local conditions that trying to develop an overall solution is not possible. As stated in Duffield et al. (1973): "The effect of local weather (i.e., rain, fog, clouds, snow, and hail, etc.) is so dominant that it governs the realizable path lengths and path reliabilities for millimeter-wave (MMW) communication links." The "floor level" (Defense Communications Agency 1979), i.e., the best that can ever be expected, includes the effects of atmospheric absorption by molecular oxygen. Even slight amounts of water vapor

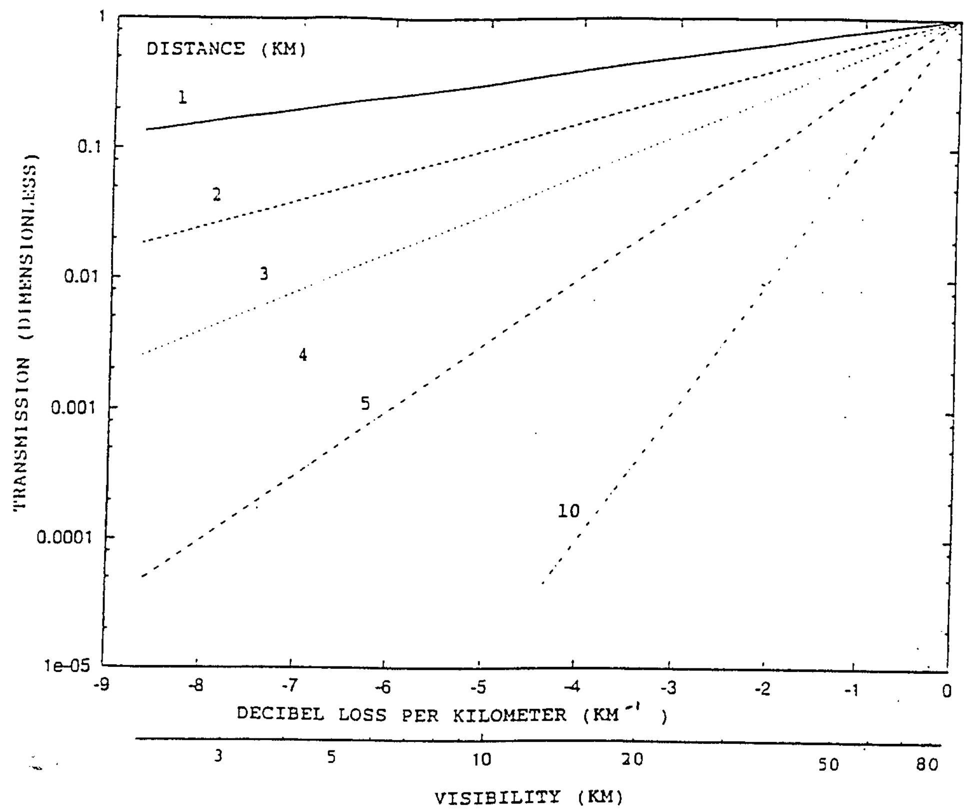

Figure 2. Relationship between optical and radio descriptors.

in the atmosphere can result in absorption at known frequencies by that compound. At high relative humidities, haze and fog can form, thereby giving rise to Rayleigh and Mie scattering. During rain events, the scattering from raindrops can be quite strong, and is a function of the point-by-point size and concentration of the raindrops. In a battlefield environment, smoke delivered by either side as well as other atmospheric contaminants, e.g., hydrocarbons, dust, and blowing sand, etc., can complicate the situation considerably throughout the electromagnetic spectrum.

The two mechanisms for the scattering of electromagnetic radiation in the atmosphere are Rayleigh and Mie scattering. The Rayleigh scattering component results from scattering by particles smaller than the wavelength of the radiation and is highly selective, i.e., wavelength dependent. It is, in fact, inversely proportional to the fourth power of the wavelength—thus in the visual spectrum, blue light is scattered much more strongly than the longer wavelengths, resulting in the sky appearing blue. The Rayleigh scattering peaks in those directions perpendicular to the direction of propagation. The Mie scattering component, on the other hand, results from scattering by particles of the same order of magnitude or larger than the wavelength. The Mie scattering coefficients were determined theoretically in the 19th century, but since they are actually the differences between the sums of very slowly converging infinite series, they

were not well known until the advent of the digital computer. Mie scattering, as opposed to Rayleigh scattering, is virtually nonselective, i.e., radiation of all frequencies is scattered with equal efficiency, thus clouds appear white. Also, as opposed to Rayleigh scattering, there are two peak directions for scattered radiation. The principal peak is in the direction of propagation; a much smaller peak is in the reverse direction. This phenomenon is responsible for the zodiacal light and gegenschein sometimes seen in the night sky that are caused by Mie scattering of solar radiation in the forward and backward directions, respectively, by dust particles in the plane of the solar system (Downs and Reitz 1975).

These factors can interfere with the successful accomplishment of point-to-point communication in several ways. First, the basic scattering and absorption by the atmosphere and its sometimes-present constituents will reduce the signal available at the receiver. Second, the backscatter by the Mie components of the atmosphere will be present at the transmitter and, therefore, if the transmitter and receiver are collocated and operate on the same frequency, will appear as noise at the receiver. Third, the forward scatter by Mie components will introduce noise at the receiver of the message recipient. Section 3.1 provides some guidelines as to usable frequencies, but it should be emphasized that there is no one frequency for which the problems imposed by the atmosphere are minimized—there is just too much normal variation.

Some examples of the amount of atmospheric attenuation in the gigahertz spectral region are shown in Figure 3 (Richard and Kammerer 1975).

In the diagram on the left, the solid line is the basic absorption curve of a normal atmosphere. Shown on the same diagram, the included points represent some normal rainfall rates. It can be seen that the rainfall can increase the attenuation of signal over a 1-km path by a substantial amount, thereby dominating the attenuation. Another way of viewing this effect is shown in the diagram on the right, which is taken from a different data set. By connecting the data points taken in transmission bands, it is apparent that the tendency is for the attenuation rate to increase with increasing frequency in both rain and fog.

Another way of characterizing the attenuation by rain at selected frequencies is shown in Figure 4 (Duffield et al. 1973).

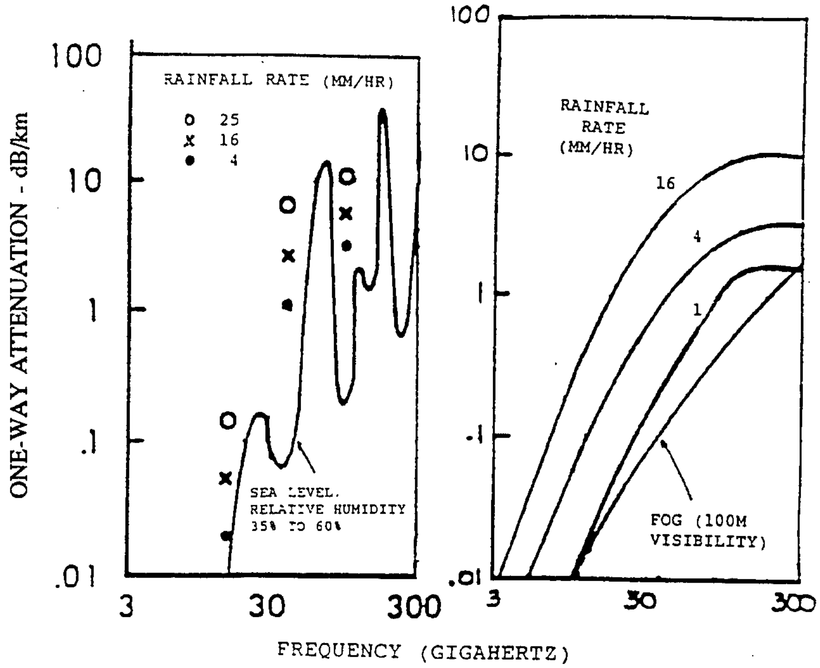

Figure 3. Attenuation by rainfall.

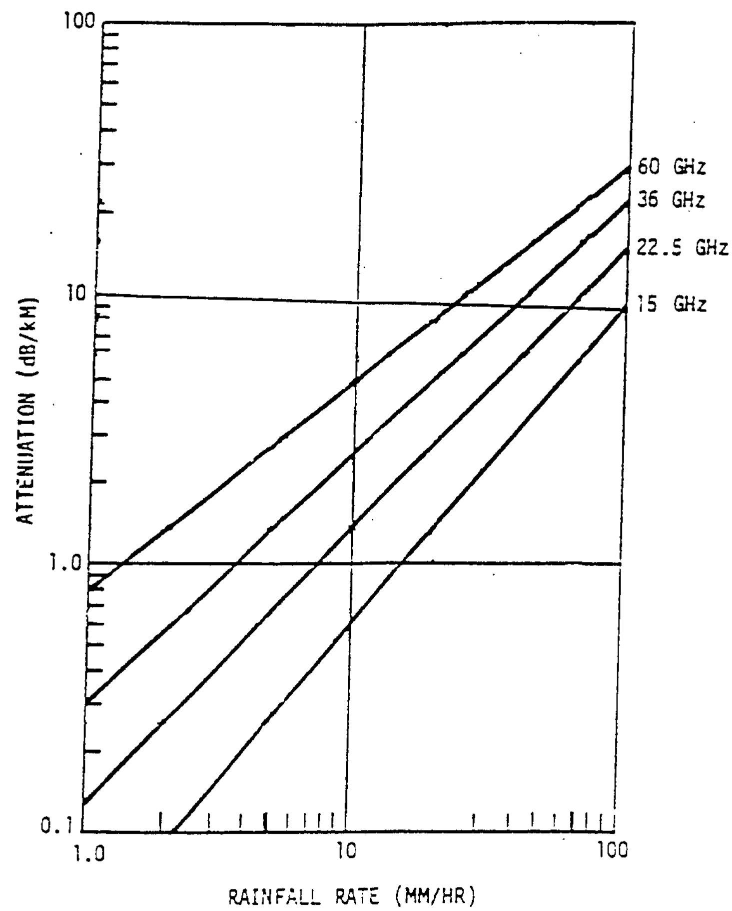

Figure 4. Attenuation by rainfall.

The second effect that fog and rain can have on propagation in the radio spectrum is electromagnetic backscatter by the fog and/or rain droplets. The extent of the backscatter problem is shown in Figure 5.

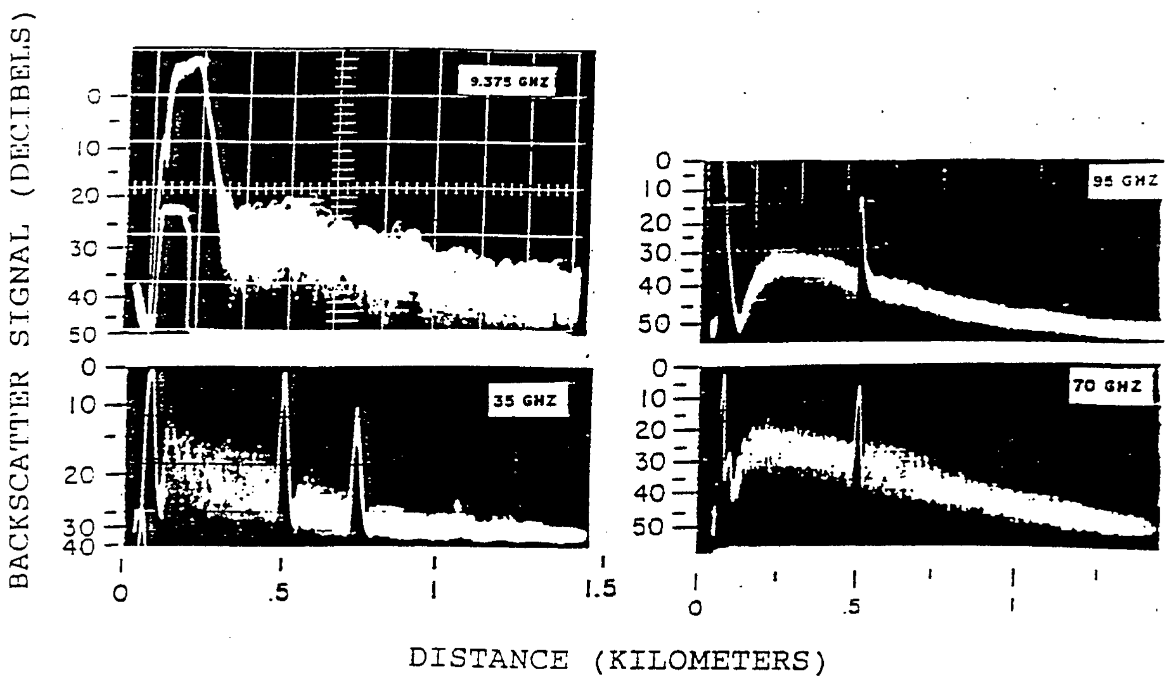

Figure 5. Backscatter by rainfall.

These measurements, taken in rainfall of an unspecified rate on the Spesutie Island area of Aberdeen Proving Ground (APG), MD, were made by photographing the screen of an oscilloscope and performing an after-the-fact analysis to determine the scales for both ordinate and abscissa. Two features stand out in this series of measurements. First, the strongest backscatter as seen at the transmitter comes from those atmospheric segments closest to the transmitter. This is due to the greater attenuation in the two-way path for atmospheric elements more distant from the transmitter/receiver. Second, the amount of noise on the backscatter curve decreases with increasing frequency. The reason for this effect is not readily apparent, but is most likely related to the fact that as the frequency increases from 10 to 100 GHz, the wavelength of the radiation decreases from 3 to 0.3 cm, thus entering the region in which the wavelength is comparable to the raindrop size. It is apparent from these measurements that if the transmitter and receiver are collocated and operate at the same frequency, self-jamming can occur and that the problem is more severe at lower frequencies at least within the range of frequencies shown.

The third effect that attenuation by water droplets can have on electromagnetic propagation is that of forward scattering. By the nature of Mie scattering, the forward scattering component will dominate the backscatter component for water droplets. The magnitude of the forward scattering effect is shown in Figure 6.

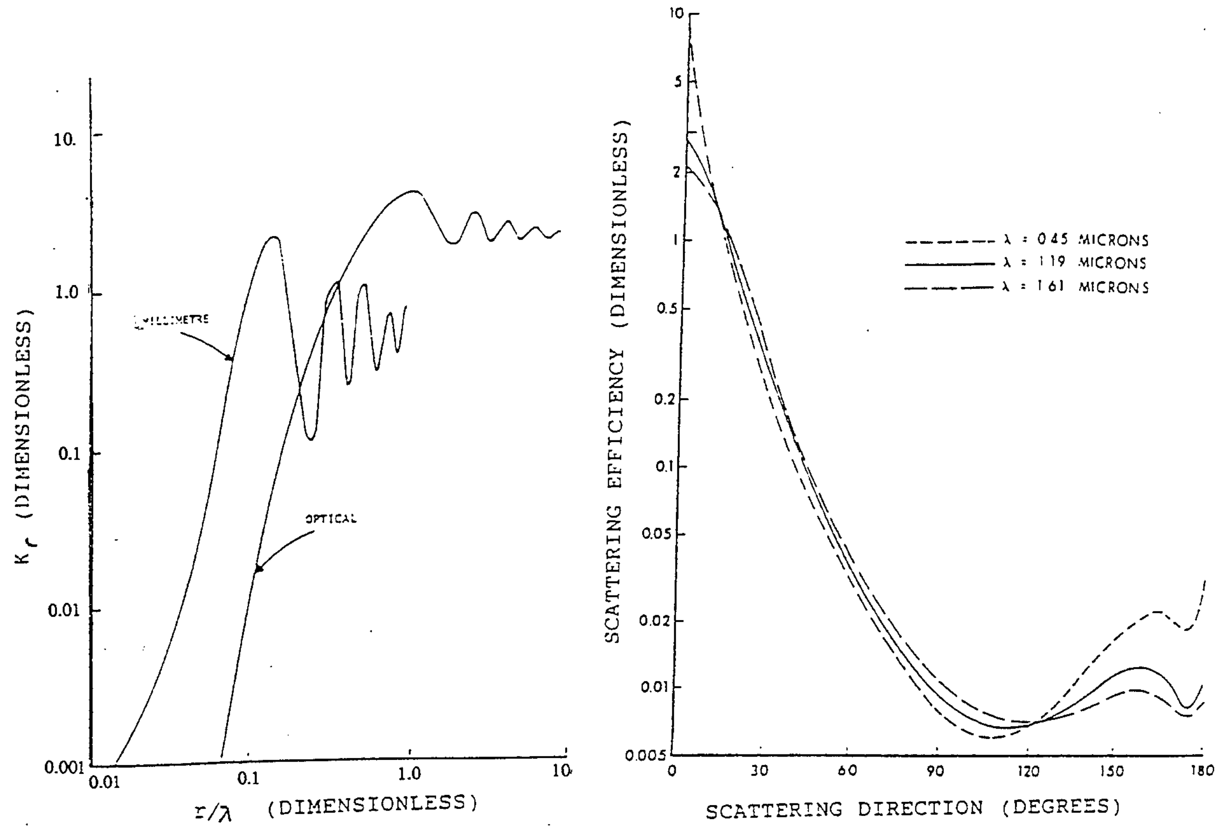

Figure 6. Mie scattering parameters.

The left set of curves (Downs 1976) shows the scattering area ratio (K_r) for water droplets as a function of droplet size. K_r is the ratio between the area removed from the wavefront by the presence of a droplet and the cross-sectional area of the droplet. The energy removed from the wavefront by multiple particles in a monodisperse (all droplets are the same size) medium is proportional to the ordinate of these curves. In a polydisperse (the droplets are distributed in size) a similar set of curves results, but with the

peaks and valleys on the right side smoothed out. The steep portion of each curve represents the Rayleigh scattering region. It is apparent from visual inspection that the nature of the curves in the optical and microwave regions is quite similar, the difference between them being the complex index of refraction of the droplet at the respective frequencies.

The right set of curves (Downs 1972) demonstrates the relative scattering efficiency for water droplets at several frequencies in the optical portion of the spectrum. The actual values of the ordinate scale pertain to the absolute amount of energy scattered into a steradian, and is thus irrelevant in this application. The difference between the three curves is a function of the complex index of refraction of water at the given wavelengths and is unimportant in this study except to note that similar curves result in the radio frequency portion of the spectrum. The abscissa in this graph is the scattering direction as measured from the direction of propagation of the prescattered radiation. The important feature to notice is the ratio between the ordinates for any one curve at the abscissa values of 180° and 0°. This feature is also present in the radio spectrum although I could not locate any graphs to document the phenomenon. The shape of these curves demonstrates that there is a very strong forward scattering lobe and a much smaller backscattering lobe. This phenomenon is very apparent when looking at the moon through a light overcast. The relevance to this study is that the forward-scattered radiation will likely take a slightly longer path to reach the receiver. The result is a multipath effect and will create interference effects at the receiver/recipient of the transmission.

It would be negligent to cover the atmospheric effects introduced by haze, fog, and rain but ignore a significant contributor to the total atmospheric interference on the battlefield—namely, smoke. The adverse effects of some exotic smokes (Downs and Reitz 1975) on the radio frequency spectrum is well known.

According to Reitz (1995), current tactics for smoke usage are primarily defensive, i.e., the use of smoke on or near friendly units to interfere with enemy acquisition or guidance systems deployed against them. There are cases in which smoke can be placed on enemy units, e.g., the use of red phosphorus to disrupt enemy activities while not interfering with friendly electro-optical systems. Such use, however, is outside the scope of the current study. A number of deployment mechanisms have been developed for smokes. These include portable, towed, and vehicle-mounted smoke generators, mortars, field artillery, multiple-launch rocket systems (MLRS), and air-to-ground rockets. The spatial and temporal properties of intentionally distributed battlefield smokes are very dependent on environmental factors as well as the

method of dissemination. The height of smoke clouds is basically governed by the wind. If there is enough thermal activity to cause the smoke cloud to rise in the first place, it will generally continue to rise until it encounters a thermal layer. The duration of a cloud is also dependent on the wind, on the type of smoke employed, and on the relative humidity; however, 60 s is a not uncommon estimate. This time can be extended indefinitely by repeated release of aerosol particulates. The lateral distribution of smoke cloud particulates is dependent on the wind and the number and spacing of locations at which such clouds are generated.

Currently available smokes are not particularly effective, i.e., not very effective obscurers, in the VHF/UHF areas of the electromagnetic spectrum but are very effective at the higher (EHF, MMW, and optical) frequencies. That their effects cannot be ignored is borne out by the fact that potential adversaries are far ahead of us in fog oil (which is effective only in the optical region) generation and closely trail us in the development of the more exotic smokes that are effective in the EHF region of the spectrum. Currently available smokes include some that will provide constant attenuation across the band from about 10 GHz through visual. These smokes can disturb operations in the radio frequency by scattering from the direct beam, absorption from the beam by graphite particles, backscatter, and re-radiation at other frequencies by iron filaments in the smoke. Some current smokes absorb all radiation incident upon it and re-radiate in the infrared. Attenuation coefficients for these smokes are functions of concentration, which is in turn a function of wind characteristics and delivery profiles. Attenuation coefficients can, however, be predicted for tactical situations when the relevant inputs are specified.

Many of the studies referenced in this report address the use of satellite relay stations. In order to place such studies in the needed perspective, it seems desirable to introduce the concept of slant-path atmospherics. The basic references (Downs 1972; Downs, Joel, and Yunker 1973) for this analysis were limited to the optical region of the electromagnetic spectrum, but the formulations and analysis provided in that report have general application and are thus pertinent to the radio spectrum as well.

The basic equation for the scattering of electromagnetic radiation passing through a medium is:

$$T = \exp(-r\sigma),$$

where T is the transmission of the medium, r is the distance traveled in the medium, and σ, with the units of inverse kilometers, is the attenuation or scattering coefficient of the medium. Since σ is composed of

both Rayleigh and Mie scattering components, it is at any single wavelength the sum of the Rayleigh and Mie scattering coefficients. Each of these coefficients is independently wavelength (frequency) dependent, so determining the scattering from a beam that contains a number of frequencies must be done by summing the scattering coefficients over a set of sufficiently narrow frequency bands when the single-frequency coefficients are weighted by the intensity of the radiation at each frequency. If σ is independent of r, this procedure is relatively straightforward. The problem is that this assumption only stands a chance of being true to within reasonable limits when the propagation path is horizontal.

If the propagation path were inclined to the horizon by an angle ϕ, and were independent of r, the forgoing equation for r, the distance to the top of the atmosphere, would be:

$$T = \exp\left(-r\sigma/\sin(\phi)\right).$$

This equation, which neglects the effect of the earth's curvature, would be true if the scattering particles were distributed evenly with altitude to the top of the atmosphere and then stopped sharply. In reality, the concentration of the scattering particles decreases with altitude. In addition, the concentration of each type of scattering particle varies with altitude in a different manner.

At this point, it seems reasonable to introduce a definition. The scale height of a particular atmospheric constituent is that horizontal distance over which the total amount of the given constituent in the path is the same as the amount of the same constituent in a vertical path that extends from zero to infinity. The scale height is thus seen to be a function of the particular type of constituent of interest. The referenced reports describe the development of a mathematical model to describe the slant path attenuation by the atmosphere and various constituents. No model can be fully predictive in this regard since the attenuation coefficient, σ, is generally a strong function of position and is not known point-by-point, even for horizontal paths. When a slant path is considered, the likelihood of knowing the concentration of scattering elements point-by-point is zero. The scale height is a prediction of the manner in which the concentration of relevant scattering elements decreases with altitude based on ground-level observable variables. Several examples of the manner in which the attenuation coefficient varies with altitude is shown in Figure 7.

The abscissa on this figure is the sum of the Rayleigh and Mie scattering coefficients. The straight line on the left is the Rayleigh coefficient alone. Such a straight line indicates an exponential rate of decrease with altitude. About all that can be said of the other lines is, in general, that above an altitude

of about 3 km, the concentration of the Mie scattering particles decreases with altitude. For a couple of high-σ curves, even this assumption is seen to be in error.

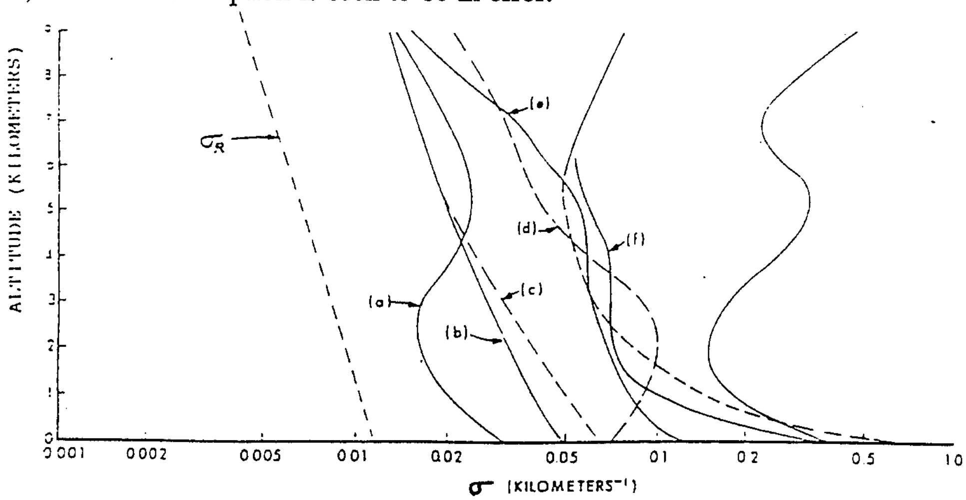

Figure 7. Altitude dependence of Rayleigh and Mie attenuation coefficients.

It is obvious from this diagram that no simple model can predict the attenuation coefficient as a function of altitude with high accuracy based on ground-level observable variables. It is possible, however, to obtain an estimate if one accepts the fact that in unusual cases, of which two are shown in Figure 7, sizable errors will result. For full details, the reader must consult the basic study (Downs 1972), but the methodology entails integration along a slant path wherein the scale height for Rayleigh scatterers is 8.0 km, that for water vapor is 5.7 km, and that for Mie scatterers when the ground level visibility is greater than G(λ) is 4.1 km. G(λ) is generally a strong function of wavelength (λ)/frequency and typically varies between 10 and 30 km. When the visibility is less than G(λ), the situation is quite complicated and entails integrating along two paths; one of which has a scale height of 4.1 km and the other having a scale height that is a complicated function of the ground-level visibility.

The amount of detail in the described model is not necessary for this study, however, since slant-path reliabilities are given in the referenced literature. Most of these reliabilities are determined based on similar models or on a limited-size data set, and the previous analysis is provided to allow the reader to estimate the uncertainties involved in such prediction.

In Townsend and Kallgren (1991), a quality analysis was performed in the 1–100-GHz band to determine the best frequencies to use in air-to-air communications. The communication links had to traverse paths through rain—the paths were sometimes as much as 240-nautical miles (444 km). A detailed analysis of the utility of using a circular directional antenna of 0.33-m^2 aperture at a frequency

of 70 GHz. Under this configuration, the first null in the antenna gain pattern occurs at 0.5°. The resulting conclusions are that designs of high-frequency systems will entail:

- smaller aperture antennas, i.e., fixed gain at higher frequencies;

- greater link power margin to allow for off-axis antenna pointing losses;

- more accurate knowledge of transmitter and receiver locations; and

- more accurate antenna pointing control.

The report concluded that these restrictions might preclude operation at those frequencies higher than the 60-GHz oxygen absorption band. The principal conclusion from the study was that ". . . frequencies in X-band (8–12 GHz) yield the best component link performance when high capacity is required and jamming and intercept threats are present simultaneously. Directive antennas are required to achieve the levels of performance we expect."

Another report (Katzenstein 1980) considered the higher 92–95-GHz band in the role of fixed-point to fixed-point transmission. Operation in this band is characterized by small (6–10 cm) antennas with narrow beamwidths and large antenna gains. The large bandwidths available at these frequencies are offset by severe limitations imposed by atmospheric effects. Ground-to-ground, ground-to-air-to-ground, and ground-to-satellite-to-ground communication links are considered. The conclusions reached include the following:

- Large increases in transmitter power are needed to achieve small increases in range. (For the applications in the present study, this is not a serious limitation since only hundreds of watts are needed for ranges of interest.)

- Except for the highly unlikely presence of a transmitter very close to the main antenna beam of an earth station transmitter or very close proximity of two mobile transmitters, reasonable minimum separations between transmitters result.

- To offset the foregoing limitation, site shielding is easy to implement and is effective at these frequencies.

- In satellite relay applications, the transmitted power must be limited to about 400 kW. (This should impose no problem in the present study.)

In Mundie and Feldman (1978), the frequency range of 20–300 GHz was addressed by considering individual frequencies of 21.2, 31, 48, 101, 152, and 265 GHz. These frequencies were selected because each is in a different band that has been selected for satellite communications and because they occupy, in their respective bands, the precise frequency at which the atmosphere poses the most severe restrictions. The basic effort behind this study was to determine performance when various key parameters are systematically varied rather than to perform an optimization study. The parameters investigated were frequency, elevation angle (10, 30, 45, and 90°), and antenna size (10 m and 10 cm). Parameters that were fixed include transmitter power (10 W), antenna efficiency (0.56), and an acceptable system margin of 8 dB. To accommodate this study, a model was developed that relates the aforementioned parameters and is applied to hypothetical communication links to estimate the statistical distribution of atmospherically induced degradation in link performance as a function of data rate and some other system parameters. The other variable considered in the report was footprint width. This variable is a measure of the area, and thus the number of users, serviced by a single beam and is used as a measure of the mutual interference problem. When the footprint is held constant, the associated satellite antenna diameter is required to decrease with increasing frequency, thereby causing a more rapid decrease in the allowable data rate with increasing frequency. This effect is counterbalanced by an increase in the number of such smaller antennas that can be mounted in the same total aperture.

The output of the study is a set of tables similar to Table 2, which was taken from the report.

Conclusions that were drawn from this study were:

- Performance degrades rapidly as the elevation angle at the user falls below 30°, especially at higher frequencies;

- For communication systems that must operate during rain, the higher the frequency, the more important it is to avoid elevation angles below 30°;

- The acquisition problem becomes major when communications must be maintained with large numbers of widely dispersed users having only small antennas, and when mutual interference rejection, covertness, and a high degree of security from jamming are required; and

- The compatibility of high-frequency communications equipment with small mobile user platforms is not compromised by the use of a 10-cm-diameter antenna.

Table 2. Satellite Link Performance as a Function of Frequency

Frequency (GHz)	4.4-m (Constant) Satellite Antenna Diameter 10^6 bps Data Rate		123 nmi (Constant) Footprint Width		
	Availability (%)	Footprint Width (nmi)	Data Rate (bps)	Availability (%)	Satellite Antenna Diameter (m)
21.2	98.7	123	10^6	98.7	4.4
31	98.9	83.8	10^6	97.5	3.0
48	96	54.0	10^5	98	1.94
101	94	25.7	10^4	97	0.92
152	94	17.1	10^4	96	0.61
265	89	9.8	10^3	94	0.35

3.2 Terrain Considerations. The effect of terrain on signal propagation has been addressed in a large number of studies of which only a sampling is covered here. As stated in Brennan (1987), "Variations in terrain greatly affect radio signal propagation, particularly at VHF and higher frequencies." This effect can result in the interruption of tactical operations and can prevent effective command and control. The referenced study used a computer model, the Ground Network Communication Model (GNCM) developed jointly by the U.S. Army Communications-Electronics Command (CECOM) and the Department of Commerce, to look into this problem at a wavelength of 1.8 GHz. This model was used to deploy radios in an actual geographic area based on elevation data taken from digitized maps provided by the Defense Mapping Agency. The GNCM was then used to calculate, link-by-link, the path loss for all possible links within this array.

In the actual study, 51 radios operating at 1.8 GHz were deployed over a 40-km × 40-km grid. The radios are then moved in steps of 200 m in random directions and the situation re-evaluated. This process was repeated 250 times. Statistics on which links could communicate at each configuration were collected.

This process was repeated in five different types of terrain. Although no definitive answers could be obtained, several conclusions could be drawn:

- In all types of terrain, signal connectivity losses occur;

- Surprisingly, greater signal connectivity losses occur in smooth terrain; and

- As the experiment progresses, there is a tendency to form clusters of intercommunicating radios that are isolated from all radios outside the cluster. Again, this effect is most severe in smooth terrain.

Another study (Nielson 1975) addressed the effects of both terrain and the urbanization level on time delay effects due to multipath phenomena at 430 MHz and 1.37 GHz. It was found that delays of 5–6 μs were not uncommon in urban environments whereas no delay was found in completely rural areas. In those areas where delays of 2–3 μs were the norm (hilly or suburban environments), there was no way of predicting the conditions that give rise to a particular delay. In urban or hilly terrain, the strongest signal does not necessarily arrive along the path with the shortest delay. Very short moves can change the path of the strongest signal, thus causing interference in a moving receiver that would not be present in a stationary one. Moving vehicles (including aircraft) in the vicinity of field operations can cause variations in the multipath character. Such variations are sufficiently slow that the loss of entire packets is more likely than the corruption of information within a packet. Impulsive noise from automotive ignition systems presents problems at both frequencies (most severe at the lower frequency) but much of the effect of such problems can be blocked with an appropriate impulse filter.

In another study (Skomal and Reed 1966), unintentionally generated manmade noise was addressed in the VHF/UHF (100–500 MHz) bands. Noise sources included internal receiver noise plus the normal noise generated in urban centers, e.g., spurious radio transmissions, internal combustion engines, etc. A 20-mile × 20-mile grid was established in Germany such that it included built-up areas. Fifteen to 150 relay stations were emplaced randomly within the grid. A message was sent from a master station and repeated up to 12 times. The dependent variable was the number of receivers that got the message properly as a function of the number of repeats. Several conclusions were drawn from the study:

- Unintentionally generated manmade noise can severely degrade the performance of fixed and mobile communication systems;

- Two to three repeats of the message generally ensure reception by every station capable of receiving it;
- Further message repetitions improve the reliability of messages received by the nearest receivers and those that pass through the fewest number of relays; but
- Such repetitions do little to get the message to the more distant receivers.

In another study (Zabodsky 1975), specifically aimed at urban environments, frequencies of 80, 150, and 450 MHz were addressed. A transmitter was fixed in location while a receiver was moved around the area. It was found that signals can vary by as much as 20–30 dB when the receiver is moved by as little as a few centimeters. It was concluded that fading and multipath effects are severe and that the magnitude of these effects decreases with increasing frequency. This conclusion was reinforced by another report (Alexe, DiPatri, and Meinert 1995) that concluded that at MMW frequencies (~10 GHz) multipath effects/interference/fading are less of a problem than at lower frequencies.

Finally, another study (Johns Hopkins Applied Physics Laboratory ~1960) analyzed the mean tank engagement ranges in Europe during World War II. This study is pertinent since the tank engagement tactics of both sides were the same—"When you see an enemy tank . . . shoot." These tactics made sense at the time since remaining motionless until the enemy was at a closer range had been demonstrated to be a losing proposition. There was too much chance that the enemy would see the motionless tank and get off the first shot. The probability of a kill with the first shot was low; however, this tactic allowed corrections to be made before the opposing tank could get off his first shot, and the probability of a kill with the second shot, even at extreme range, was too great to be discounted. Based on these tactics, the range at which the tanks were engaged is also a measure of the intervisibility distance in that area. Since these engagement ranges were known, statistics could be generated on the intervisibility distance from the engagement reports.

It should be noted that the distances involved were, in general, true sample intervisibility distances since conditions other than chance encounter (e.g., tanks in defilade or in preselected positions) were not considered in the study. The basic conclusion of this study was that the engagement ranges could be represented by a Pearson III distribution with a mean of 728 m and a variance of 310 m. The two-

parameter Pearson III distribution reduces to a Gamma distribution. The Gamma distribution with the mean and variance as given is shown in Figure 8.

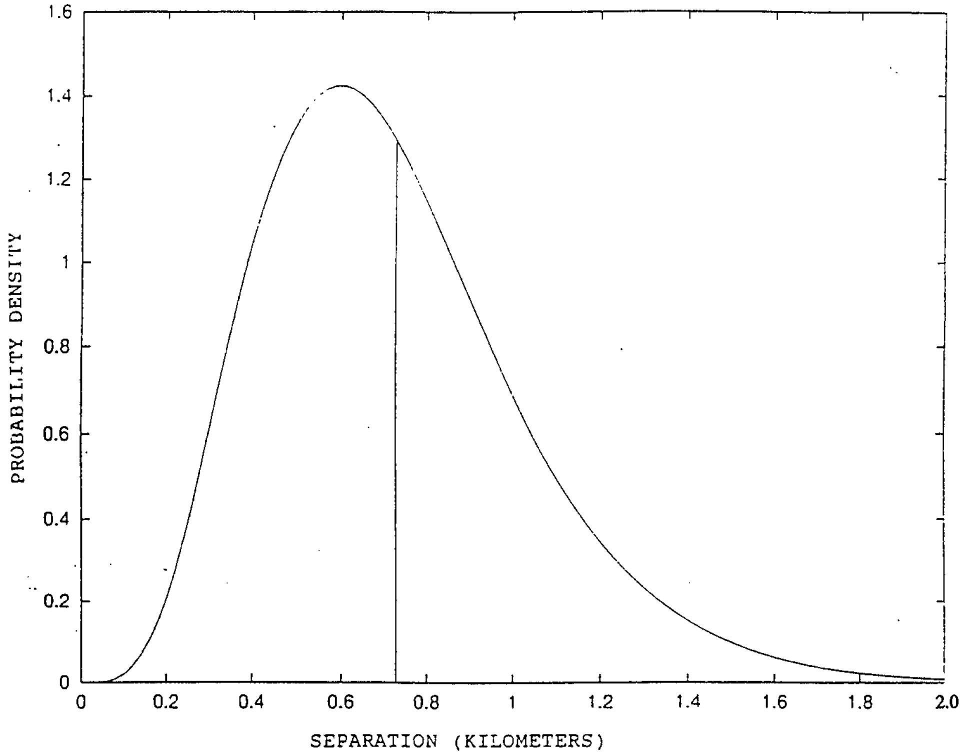

Figure 8. Gamma distribution with mean of 728 m and variance of 310 m.

The mean of this distribution is indicated by the vertical line. It can be seen that the most likely intervisibility distance is less than the mean, and is around 600 m. It is also apparent that the likelihood of an intervisibility distance in excess of 2 km is vanishingly small.

3.3 Other Considerations. VHF, UHF, and EHF links all exhibit problems that result from their line-of-sight nature (Sundaram 1988). Natural and manmade obstacles can seriously degrade communications in both the ground-to-ground and air-to-ground modes. Satellite links can overcome most of these limitations. Additional advantages offered by satellite communication links include:

- They are extremely reliable;
- The network can be reconfigured rapidly and easily;
- They are not affected by distance, terrain, or other obstacles;

- Depending on the operational frequency band, available bandwidth can be extremely high;

- Large numbers of users can be accommodated; and

- Data rates are limited only by the satellite's transmitter output power and the sensitivity of the ground receiver.

The use of EHF frequencies in conjunction with satellite links offers additional advantages. The very small size of the components in EHF bands reduces the size and weight of the needed portable and vehicular terminals. In addition, the transmitted beams are so narrow that the problems that potential opponents would encounter in monitoring/jamming friendly communications are confounded.

The DOD is in the process of developing the MILSTAR EHF MILSATCOM system. This system is the first to operate in the millimeter region of the spectrum and is planned to operate with a 44-GHz uplink and a 20-GHz downlink. This system is highly survivable and has virtually unlimited capacity. A network of eight satellites is envisioned as this is sufficient to provide near global coverage for both strategic and mobile tactical subscribers. This satellite network is expected to become operational in the mid-1990s.

An investigation into the feasibility of using EHF bands to handle ground-satellite communications is described in McElroy and Eaves (1980). The investigation was addressed primarily at assessing tradeoffs in satellite weight, communications capacity, and frequency between 20 and 60 GHz. The recommendations were that there is a great deal of promise for systems in the lower part of this frequency band, i.e., 44-GHz uplinks and 20-GHz downlinks, but that higher frequencies are uncertain because of atmospheric considerations.

The number of communication channels available in various parts of the radio spectrum were presented in Almetlaq (1989). The bands that were addressed in this reference are different from those in Dorf (1993) but were selected to nominally fit those of the HF, VHF, and UHF bands. In order to provide a comparison between this information and similar information in the EHF band, the information in the reference was extrapolated and the combined results presented in Table 3.

Table 3. Communication Channel Availability in Various Radio Bands

Nominal Band	Frequency Range (MHz)	No. of Available Channels
HF	2–30	9,000
VHF	30–88 plus 110–150	3,680
UHF	225–400	7,000
EHF1	1,000–10,000	1,460,000
EHF2	10,000–30,000	8,960,000
EHF3	30,000–60,000	27,000,000
EHF4	60,000–100,000	125,000,000

If the information in Almetlaq (1989) is correct, the width of an individual communication channel is a nonlinear function of the square of the frequency. The nonlinearity is not so severe as to prevent extrapolation; however, the process of extrapolation does introduce an error. The final four entries in the last column, therefore, should not be considered definitive, but are close enough to reality to demonstrate the main conclusion of this example—namely, that the channel availability in the EHF band is effectively unlimited.

Even though published in 1978, Mundie and Feldman (1978) presents some useful information on various issues pertinent to this study. With respect to the problems of pointing and tracking, it states: "For small mobile users, the decrease in terminal antenna diameter (to 10 cm) . . . more than compensates for the increase in frequency, so that terminal pointing and tracking are considerably relaxed. The increased pointing and tracking accuracy required by the wide-band data relay user at higher frequencies can be provided by current techniques." The report then points out that although the necessary satellite attitude reference system is more complex at higher frequencies, the relative incremental cost is small. The Space Sextant-Attitude Reference System, which was then under development, was expected to provide a substantial accuracy improvement (0.0004°) with no increase in cost. The data rates available in such circumstances are seen in Table 2 to be between 100,000 and 1,000,000 bps if the selected frequency is below the 60-GHz oxygen absorption band.

Pankow (1977) is primarily a push for the development of digital radios, but does contain a few additional useful pieces of information as well. It points out that high-quality digital transmissions can be supported if the bit error rate is of the order of magnitude of 0.0001. This corresponds to an average signal-to-noise ratio of 11.4 dB in the absence of fading. In the presence of fading that obeys a Rayleigh distribution, the average signal-to-noise ratio increases to about 37 dB. This effect can be mitigated by multiple transmissions. It has been shown (Rustako 1973) that if the number of repetitions is 3 or 4, the results will be similar to those in which no fadings occur.

The Battlefield Information Distribution (BID) concept has been developed by CENCOMS (Blackman 1982) to address the U.S. Army Training and Doctrine Command (TRADOC) Air Land Battle 2000 concept. There are several main elements in BID, the first being survivability. This is provided by a decentralized network management structure and a robust signal waveform. The second element is data integrity, security, and data transmission reliability. The reliability of the data is achieved through the use of a robust set of communication protocols operating within the network to provide the user with nearly error-free data transmissions. (The criterion for nearly error-free is a bit error rate less than 10^{-12}, which is a much tighter limit than was found to be appropriate in Pankow [1977]. The likelihood that this value could ever be achieved in practice over a tactical radio is exceedingly small.) The third element is that of an inter-network architecture. The implication of such an architecture is that "a variety of transmission media, such as broadcast radio, satellite, terrestrial multichannel radio, and fiber-optic cable, are all integrated via a network management structure and architecture into a coherent real-time communication network." It further points out that communications in the millimeter region of the spectrum provide advantages in the areas of frequency availability, wide bandwidth, small component size, and small visual and RF signatures and that technology in the frequency bands below 60 GHz is already well advanced and that such systems could proceed into immediate development. Among the stated applications for such systems are short-range multichannel operations and dispersed command-post communications.

In the middle megahertz frequencies, e.g., 150 MHz, some information on field operations is provided by Suchy (1961). The configuration addressed was a fixed command post and a mobile station communicating via fixed repeater stations. It was observed that when a transmitter and repeater or two repeaters are in simultaneous operation, there is an area between them where there is an apparent distortion in reception to a mobile station trying to monitor the output of either station. This distortion lies roughly in the equal-power region, but the size and shape is heavily influenced by the specifics of the terrain. This area of distortion can be minimized by shading of the fixed stations by terrain obstacles and can be

eliminated by using different frequencies, but both of these options have tactical repercussions that must be weighed. It was determined that increasing the power of the command-post transmitter did not improve the quality of the communications if the unboosted power was already adequate for communications. All that resulted was providing a more intense source to attract hostile monitors/jammers and changing the locations of the communications distortion areas. It was found that in the rather undulating countryside of Czechoslovakia, if a transmitter power of 30 W was employed, spacings of 20–30 km between repeater stations provided communications of acceptable quality if the locations of the stations were carefully selected. For any use of a satellite relay, there will be a number of noise sources that compete with the satellite transmissions (Hayden 1970). Some of these noise sources are:

- Manmade Noise - ". . . surface noise in an urban location can be expected to exceed that of an ideal receiver . . . for frequencies up to and greater than 1,000 MHz."

- Thunderstorm Noise - "These noise levels exceed those for receivers of good design in the VHF range." They do not generally present a problem in the UHF or EHF spectral regions.

- Galactic Noise - "Galactic noise sources may be expected to contribute significant noise power to receiver systems operating below about 100 MHz even when simple receiver antennas are used."

- Solar Noise - "During daylight hours the quiet sun contributes insignificant noise to receiver systems using simple antennas. However, the noise may be significant during disturbed conditions." Such disturbances can last for periods greater than an hour.

- Atmospheric Absorption Noise - This effect can exceed internal receiver noise at frequencies less than about 50 MHz.

The relationship between the power requirement and the size of the antenna is presented in Figure 9 taken from Richard and Kammerer (1975).

In all four cases, the rainfall rate was 70 mm/hr, corresponding to a reasonably intense rainfall, and link reliabilities were between 99.5 and 99.9%. The data rates over the indicated links were 2.3, 20, 160, and 236 Mb/s for the 15-, 22.5-, 36-, and 60-GHz frequencies respectively. It should be further noted that

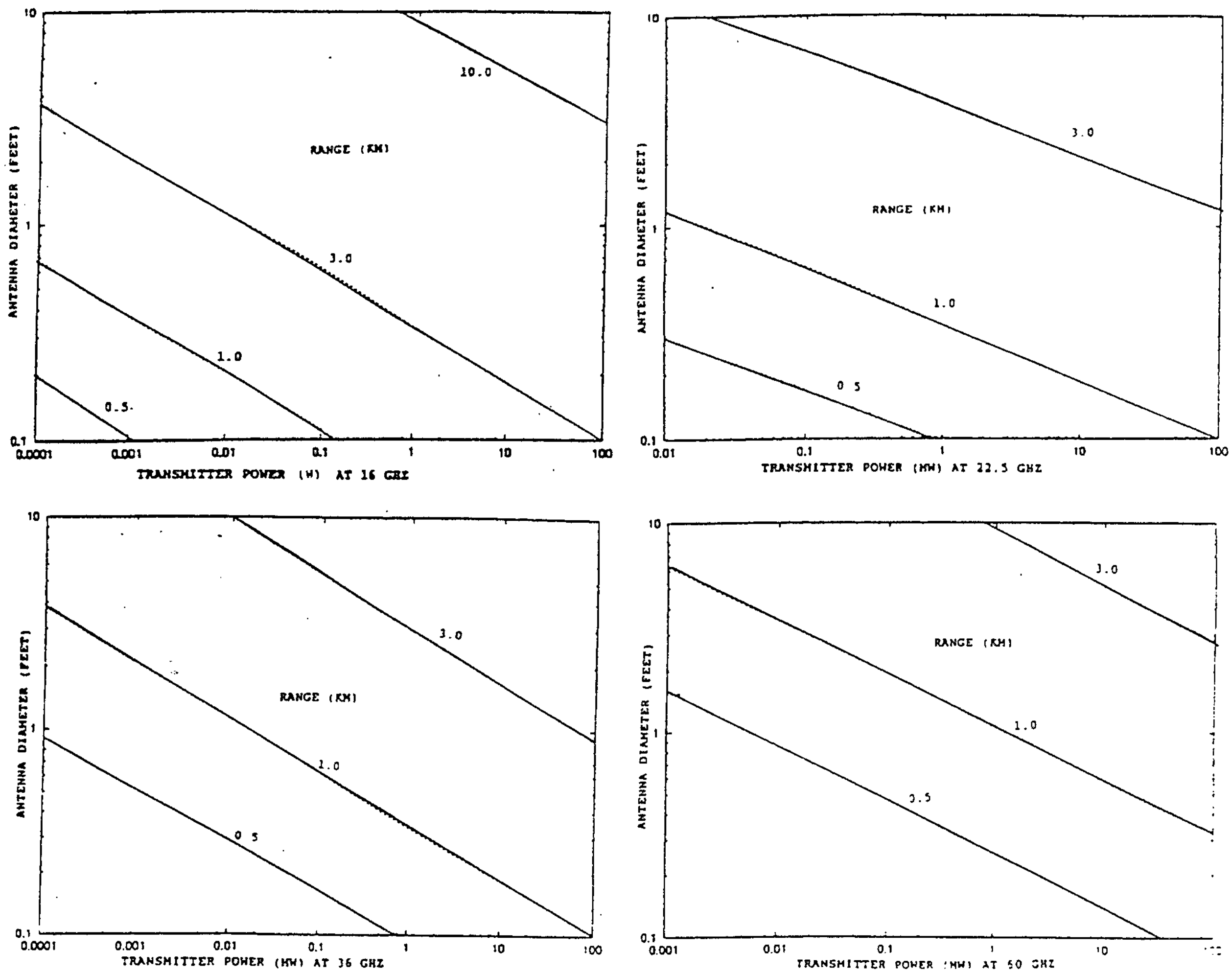

Figure 9. Relationship Between Antenna Size and Power Requirements.

the frequencies used in this study were selected to represent the most restrictive atmospheric conditions. This has the effect of limiting the range at which the signal can be detected, thus confounding the ability of a potential adversary to monitor or jam the transmission. Even with the limited range and the transmitter powers shown, it is apparent that with a realistic antenna size, e.g., 2 ft, sufficient range can be obtained at these frequencies to provide a viable capability except at 60 GHz, which is in the middle of a deep oxygen absorption band. While powering capabilities of only 5 W were available in 1973 (when the reference was published), ample power is now available to use any of these frequencies. The frequencies between those provided would require even less power, so it can be stated that power requirements are not a limiting factor in selecting desirable frequencies. Additional information provided

in Richard and Kammerer (1975) include the expectations that a "burst" data rate of 25 Mb/s should be possible for the frequencies indicated and that a bit error rate of 10^{-6} should likewise be possible.

Because of the classified nature of most useful information about countermeasures, little useful information on jamming was available to include in this report. Almetlaq (1989) does present some information on the types of jammers—barrage and spot—and the types of signals available for each, to include random-keyed Morse code, pulse, recorded sounds, gulls, random noise, stepped tones, random pulse, spark, wobbler, and rotary. Because of the efficiency of currently available jammers, directional antennas are almost mandatory. The International Defense Review (1986) provides some basic information on current U.S. jammers. A number of companies including Rohde & Schwartz, Watkins-Johnson, Sanders, and HRB Singer have developed jamming systems for the U.S. Armed Forces.

The Rohde & Schwartz system exhibits extremely high performance in the 2–500-MHz spectral region with extension to 1.3 GHz available. Using monopulse techniques, it can detect and locate a radio frequency emitter within 1 μs and can detect frequency-hopping transmissions and handle rates up to 1,000 hops/s. The same company also produces the EB100 Miniport receiver, a portable, battery-operated, microprocessor-controlled midget VHF/UHF surveillance receiver. This system operates in the 20–1,000-MHz frequency range and can operate in a 30-preset-channel or frequency-scanning mode. Its WJ-8610 strategic surveillance system is a compact unit that covers a frequency range of 20–500 MHz with a frequency extension option of 2–1,100 MHz. HRB Singer's Chief covers a frequency range of 0.5–500 MHz, expandable to 1.2 GHz. Up to 12 transmitters can be targeted simultaneously with up to 2 kW of power. Airborne monitors/jammers that, in one case, extend the frequency coverage to 18 GHz are also available.

Defense Communications Agency (1979) contains a wealth of useful information; most of it, however, is classified. There were some useful unclassified tidbits. The major reason for considering higher frequency bands is the need for more channels for ground-satellite communications. For this purpose, the frequencies above 8 GHz seem to be particularly attractive and frequencies above 20 GHz are considerably more difficult to jam than those in the UHF and 7–8-GHz regions.

4. CONCLUSIONS AND RECOMMENDATIONS

The objective of this study as stated in section 1 was to perform a state-of-the-art survey to determine what new frequencies in the radio spectrum could be used for military (Army) applications and to determine some of the technical characteristics of those frequencies. In developing this report, the most sensible way of approaching this objective was considered to be the answering of the following questions.

- What regions of the electromagnetic spectrum (30 MHz and up) are potential regions for future tactical communications systems?

- Which of these regions offers the most promise for viable communications in the reasonably near future, i.e., based on today's technology?

- What tactic of employment makes the most sense, i.e., is likely to provide the best results?

- How does the effectiveness of this selected frequency/tactic compare with that of the current system used for battlefield communications?

So far in this report, a lot of loosely connected information has been presented for various wavelength bands. Some of the information has been concrete and well-defined, while other parts have been primarily subjective. It seems best at this point to compare the information in a subjective manner. This is done by first presenting three tables that represent the three basic tactics (direct line-of-sight communication, communication through ground-based relay stations, and communication through a space-based, i.e., satellite, relay station). The most promising frequency for each tactic is then compared to the system in current use, and some concluding remarks are made.

A subjective comparison of the various bands using no directional antennas and no relays is shown in Table 4.

Table 4. Prospects of a Viable Communication System Using No Directional or Relay Techniques

Factor	Frequency Band				
	30–300 (MHz)	300–1,000 (MHz)	1–20 (GHz)	20–60 (GHz)	60–100 (GHz)
Natural Atmosphere	Good	Good	Moderate	Moderate	Poor
Smoke	Moderate	Moderate	Moderate	Moderate	Moderate
Terrain	Poor	Poor	Poor	Poor	Poor
Channel Capacity	Poor	Fair	Excellent	Excellent	Excellent
Data Rate	Good	Good	Excellent	Excellent	Excellent
Bit Error Rate	Good	Good	Good	Good	Good
Interference Effects[a]	Poor	Fair	Moderate	Good	Good
Countermeasure Avoidance	Poor	Poor	Moderate	Good	Good
Size/Weight Constraints	Moderate	Good	Excellent	Excellent	Excellent
State of the Technology	Excellent	Excellent	Good	Good	Moderate
Overall Prospect	1.7 Moderate–	1.7 Moderate–	2.6 Good–	2.8 Good	2.5 Moderate+

[a] Includes effects of distortion, multipath, fading, and noise.

A ranking of Excellent, Good, Moderate, Fair, or Poor was used in this analysis. Also, a numerical ranking of 4, 3, 2, 1, or 0, respectively, was applied to the subjective rating given, and the numerical ratings were summed and averaged to obtain the overall rating. This technique has no real validity since the subjective ratings are not really defined objectively and the technique assumes that all rating elements are weighted equally, but it does have the advantage of being an interpretation aid. It is seen from this table that, viewed in isolation, the bands above 1 GHz seem to offer the best solution and that of these bands, the one between 20 and 60 GHz offers slightly better prospects. It should be remembered that this analysis is appropriate only for the case that no directional antennas or relay stations are employed.

A subjective comparison of the various bands using directional antennas in concert with ground-based relay stations is shown in Table 5.

Table 5. Prospects of a Viable Communication System Using Ground-Based Relay Stations and Directional Antennas

Factor	Frequency Band				
	30–300 (MHz)	300–1,000 (MHz)	1–20 (GHz)	20–60 (GHz)	60–100 (GHz)
Natural Atmosphere	Moderate	Moderate	Fair	Fair	Fair
Smoke	Moderate	Moderate	Moderate	Moderate	Moderate
Terrain	Moderate	Moderate	Moderate	Moderate	Moderate
Channel Capacity	Poor	Fair	Excellent	Excellent	Excellent
Data Rate	Good	Good	Excellent	Excellent	Excellent
Bit Error Rate	Good	Good	Good	Good	Good
Interference Effects[a]	Poor	Poor	Fair	Moderate	Moderate
Countermeasure Avoidance	Good	Excellent	Excellent	Excellent	Excellent
Size/Weight Constraints	Moderate	Good	Excellent	Excellent	Excellent
State of the Technology	Excellent	Excellent	Good	Good	Moderate
Overall Prospect	2.1 Moderate	2.4 Moderate+	2.8 Good	2.9 Good	2.7 Good–

[a] Includes effects of distortion, multipath, fading, and noise.

In comparing Tables 4 and 5, there are several things to notice. First, by adding the directional antennas and relay stations, the only rating elements affected were "Natural Atmosphere," "Terrain," "Interference Effects," and "Countermeasure Avoidance." The effects of the atmosphere are actually made worse since the use of one or more relay stations entails a longer path along the ground that the radiation must traverse, and as this process occurs in discrete steps, the chance of unrecoverable corruption of data is multiplied by the number of segments in the path. The ability to avoid terrain obstacles is, however, increased since this is the major reason for considering ground-based relays in the first place. The interference effects are less likely to be a problem since the directional antennas will eliminate some of the worst side effects. The ability to monitor/jam the transmission is made much more difficult by the use of directional antennas since to perform a countermeasure mission against this transmission system it would be necessary for a potential adversary to be located within the cone of the transmitting or

receiving directional antenna. Smoke has no influence on the choice since it is generally localized and will not affect the entire transmission path. The other rating elements should not be affected since they are based on physical/technological properties that are unaffected by the environment or the methods of employment addressed in these tables. It is seen that the 1–20-GHz and the 20–60-GHz bands are still slightly more effective than the other frequencies.

A subjective comparison of the various bands using directional antennas in concert with a space-based, i.e., satellite, relay station is shown in Table 6.

Table 6. Prospects of a Viable Communication System Using a Space-Based Relay Station and Directional Antennas

Factor	Frequency Band				
	30–300 (MHz)	300–1,000 (MHz)	1–20 (GHz)	20–60 (GHz)	60–100 (GHz)
Natural Atmosphere	Good	Good	Moderate	Moderate	Fair
Smoke	Good	Good	Good	Good	Good
Terrain	Good	Good	Good	Good	Good
Channel Capacity	Poor	Fair	Excellent	Excellent	Excellent
Data Rate	Good	Good	Excellent	Excellent	Excellent
Bit Error Rate	Good	Good	Good	Good	Good
Interference Effects[a]	Moderate	Moderate	Moderate	Moderate	Moderate
Countermeasure Avoidance	Excellent	Excellent	Excellent	Excellent	Excellent
Size/Weight Constraints	Moderate	Good	Excellent	Excellent	Excellent
State of the Technology	Excellent	Excellent	Good	Good	Moderate
Overall Prospect	2.7 Good–	2.9 Good	3.2 Good	3.2 Good	3.0 Good

[a] Includes effects of distortion, multipath, fading, and noise.

In comparing Tables 5 and 6, it is apparent that a satellite relay improves the situation significantly for natural atmospheres, smoke, and terrain. This effect results from the slant path entailed by the ground-space link since (1) the radiation traverses less of the near-earth atmosphere where the transmission/

scintillation effects are the most severe; and (2) the radiation is less likely to impact a terrestrial barrier on the relay-mobile transmitter link. The interference effects and countermeasure avoidance capability are also seen to provide additional benefits since the transmitter of the mobile units are less likely to produce a transmission that will intersect the terrain; thus multipath effects are less likely.

This report would not be complete without presenting some information about the system that is currently used to provide battlefield communications. This system is the Single-Channel Ground-Air Radio System (SINCGARS). Some of the pertinent characteristics of SINCGARS are provided in Table 7. The information in this table was taken from the Department of the Army (1992); Alexe, DiPatri, and Meinert (1995); and Fox and Cooper (1991).

Table 7. Pertinent SINCGARS Characteristics

Characteristics	Value
Operating Frequency	30–88 MHz
Number of Channels	2,320
Data Rate	≤16 kb/s
Countermeasureability	Significant
Bit Error Rate	10^{-6} (claimed)

From this table, it can be seen that SINCGARS falls in the 30–300-MHz band, represented by column 1 in Tables 4, 5, and 6. It can also be seen that SINCGARS operation could be slightly improved by the use of directional antennas and relay stations, particularly satellite-based. Its performance could be improved even more by switching to a higher frequency, i.e., the 1–60-GHz range. This, however, does not tell the full story since the aforementioned tables are subjective. The main reason for looking at other frequencies is that the current SINCGARS band is overloaded, thereby resulting in communication delays and low throughput. The consequences of using a transmitter/receiver that operates in the low-gigahertz portion of the radio spectrum could produce a sizable improvement in performance that is not reflected in these tables. The MILSATCOM selection of 44 GHz and 20 GHz for its uplink and downlink, respectively (Sundaram 1988), appears to be an excellent choice.

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The combat radio used by the fighting units (battalion and below) of the U.S. Army is the Single-Channel Ground/Air Radio System (SINCGARS). This radio system operates effectively except that the available bandwidth is insufficient to avoid channel congestion on digital channels, resulting in low throughput and long delays in ordinary tactical situations. This report describes one of a pair of studies that addressed one possible way to ameliorate this situation, i.e., changing the frequency at which the basic combat radio operates. This study addresses taking advantage of the higher bandwidth available in higher frequency parts of the radio frequency spectrum. The procedure entailed addressing the technological and environmental factors that affect radio operations at frequencies between 30 MHz and 100 GHz for several modes of operation, i.e., direct transmission, terrestrial relay, and satellite relay. The most favorable such system is then compared to the SINCGARS system. Several conclusions and recommendations are then presented.

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